Accelerated Full Scale Fatigue Testing of a Small Composite Wind Turbine Blade using a Mechanically Operated Test Rig

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ABSTRACT

A 2.5m long glass fibre reinforced plastic composite wind turbine blade was fatigue tested by means of a mechanically operated test rig. The rig uses a crank eccentric mechanism to flex the blade by a constant displacement in the flapwise direction for each load cycle. A yearly fatigue-loading spectrum for the blades has been developed from using short-term detailed aeroelastic and wind measurements, results from a detailed finite element model of the blade and averaged long-term wind data form the Australian Bureau of Meteorology. This spectrum contained over 200 load levels covering R ratios from 0 to 0.9. An equivalent damage spectrum has been formulated to minimise the number of load levels within the spectrum without compromising the amount of damage done to the blade structure. Results of fatigue testing indicate that predictions are close to the measured fatigue life of the blade. The stress distribution in fatigue critical areas of the blade during testing was found to be similar to the expected stress distribution under normal operational condition.

2. INTRODUCTION

A full-scale fatigue test of a wind turbine blade is considered an essential part of verifying the design of any new wind turbine blade. Wind turbine blades experience a range of complex forces throughout their working life, Eggleston and Stoddard (1987), and as such it is not possible to simulate exactly these conditions in any accelerated laboratory experiment. There are currently two methods used for the accelerated fatigue testing of large wind turbine blades: through the use of eccentric rotating mass (shaker) to vibrate the blade close to its natural frequency of vibration and using hydraulic actuators to flex the blade, van Delft and van Leeuwen (1994). Of the two methods flexing the blade using hydraulic actuators will simulate the fatigue loading more realistically.

Both the shaker and hydraulic actuator systems are applicable for the testing of small wind turbine blades. Hydraulic actuators, however, are more suited to large blade testing as the flexing forces are high and the flexing frequency low. In comparison the flexing forces for blades of small wind turbines, that is from machines with rated output power of less than 50kW, are low and the flexing frequency high given the higher speed of rotation and the inherent higher natural frequency of vibration of the smaller blade. A hydraulic system could be built for small blade testing but it would be relatively expensive both to build and operate. As such a mechanically operated blade flexing system was built for a small fraction of the cost of a hydraulically operated system. Unfortunately there is one major drawback with the mechanical system: each flexing cycle is a constant displacement cycle whereas during normal blade operation, each flexing cycle is essentially a constant force cycle. This distinction is important when the blade structure starts to fatigue, as it will flex further under a given loading regime. This limitation could be overcome by measuring the maximum force applied to the blade in each flexing cycle. Aspects of the mechanically operated fatigue test rig will be discussed in this paper.

Fatigue loading spectrums have been developed for the blades of large wind turbines based on detailed field measurements. The aeroelastic response of 2.5m blades is likely to different to that of large blades due to geometric differences in key stressed areas of the blade, Bechly and Clausen (2001), overall size and operational differences. A fatigue spectrum has been specifically developed for the 2.5m long blade based on measured aeroelastic blade response data, predictions from a detailed finite element model of the blade and long-term average wind data from the Australian Bureau of Meteorology, Epaarachchi (2002). The resulting fatigue procedure had flexing cycles in over 200 load levels at stress ratios ranging from 0 to 0.9 inclusive. Trial studies indicate that considerable time was needed to setup the test rig at each stress level and R ratio. Using the equivalent damage concept, a loading spectrum was devised which resulted in the same amount of damage to the blade structure using fewer load levels and only one R ratio. Aspects of this formulation will be presented in this paper with predictions compared to strain gauge measurements.

3. EXPERIMENTAL PROCEDURE

3.1 Test Rig

The mechanical test rig, shown in Figure 1, flexes the blade in a sinusoidal manner in its flapwise direction to a prescribed maximum displacement in each cycle.

Figure 1 Fatigue test rig.

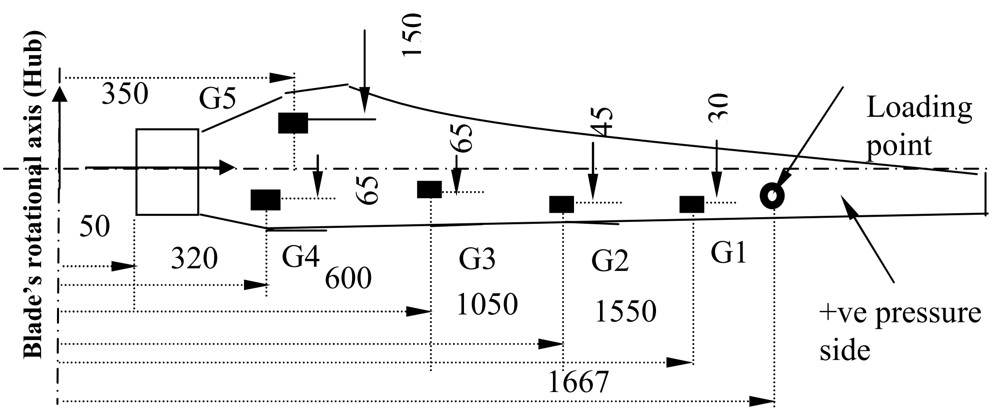

Figure 2 Location of strain gauges on the blade +ve wind direction

The maximum displacement can be altered by adjusting the eccentric radius on the crank. The horizontal arm of the test rig isolates the blade from the horizontal load component from the crank.

The arm linking the horizontal arm to the blade has been strain gauged and the blade was strain gauged at the locations shown in Figure 2.

3.2 Loading Spectrum

As previously stated a loading spectrum for full-scale fatigue testing of the 2.5m blade has been developed by Epaarachchi [2002]. Here a detailed finite element (FE) model of 2.5m wind turbine blade was built and validated against strain gauge measurements from a blade on an operating prototype wind turbine. The predictions from the FE model were used to establish the wind turbine's response over a wide range of wind speeds, other than those measured in the prototype wind turbine. The spectrum is based on the stresses at the most critical section of the blade and consists of 200 loading levels at stress ratios R ranging from 0 to 0.9 for a total of 1803705 cycles in one year of operation; Table 1 shows a part of proposed loading spectrum.

Stress Level (MPa)	**Cycles**			
	R=0.0	**R=0.1**	**R=0.2**	**R=0.3**
35.15	58	842	3524	9652
41.18	34	681	2848	7681
49.12	26	538	2096	5730
57.82	16	376	1490	4022
67.27	42	237	959	2632
77.45	40	157	610	1634
88.42	20	81	354	939
100.11	18	52	193	510
112.53	26	41	104	271

Table 1. A part of developed fatigue loading spectrum

To reduce the time for blade testing, we decided to follow the equivalent spectrum analysis method described by Sutherland [1999] and Freebury and Musial [2000] to develop a fatigue equivalent but less time consuming test cycle. The equivalent damage concept shows that an equivalent number of cycles, n, at an arbitrary stress level of σ, can be determined which causes the same amount of damage $D(\sigma_1,n_1)$ where $D(\sigma_1,n_1)$ is the damage caused by fatigue loading of σ_1 and cycles n_1. The damage at stress level σ_k, is defined by

$$D_{\sigma_k} = \frac{\sum_{r=1}^{k}\left(\sigma_{res(r-1)} - \sigma_{res(r,n_r)}\right)}{\left(\sigma_{ultimate} - \sigma_k\right)} \qquad (1)$$

Here, $\sum_{r=1}^{k}\left(\sigma_{res(r-1)} - \sigma_{res(r,n_r)}\right)$ is the strength degradation due to the spectrum loading. The residual strength after stress level, σ_i, can be shown to be given by, Epaarachchi (2002,2003):

$$\sigma_{ultimate} - \sigma_{res(n)} = \alpha\left(\frac{\sigma_i}{\sigma_{ultimate}}\right)^{0.6}\left[\sigma_i(1-R)^{1.6}\,]\,\frac{1}{f_i^{\beta}}\left(n_i^{\beta}-1\right)\phi_{n_i}\right] \qquad (2)$$

where R - stress ratio $\left(\frac{\sigma_{\min}}{\sigma_{\max}}\right)$, α, β - material constants, σ_{max} - maximum applied stress in loading direction, $\sigma_{ultimate}$ - ultimate stress of the virgin material in the loading direction, $\sigma_{(r-1)}$- *remaining* strength of material after the rth load level, $\sigma_{(r,n)}$ remaining strength of material after n cycles at rth load level, σ_k applied stress level of k th load level , f_i loading frequency at i th load level and ϕ_{ni} is defined as a factor for regain strength which is defined as [Epaarachchi (2003)] $\phi_n = 1 - \left[1 - \left(\frac{n}{N_{\sigma n}}\right)^{\beta}\right]^{\beta}$

where $N_{\sigma,n}$ is the residual life at σ_n after the loading at the (n-1)th step, which can be calculated from the Equation (1) as follows:

$$\sigma_{res(n-1)} - \sigma_n = \alpha\left(\frac{\sigma_{max}}{\sigma_{res(n-1)}}\right)^{0.6}\left[\sigma_n\ (1-R)^{1.6}\right]\frac{1}{f^{\beta}}\left(N_{\sigma\, n}{}^{\beta} - 1\right). \tag{3}$$

All cross-sections through the blade have a sandwich type construction with the skin lay-up [WC $(0^0/90^0)/0_3{}^0/90^0/0^0/\pm45^0/90^0/0_4{}^0$] having an asymmetric configuration. Fatigue tests were done on coupons of the skin material to determine material parameters for equation (2) (Epaarachchi (2000)); α and β were estimated to be 0.022414 and 0.413 respectively.

The equivalent number of cycles, $n_{quivalent}$, at stress level σ, frequency f, and stress ratio R which causes the same strength degradation at any arbitrary condition, such as stress level σ_i, frequency f_i, and stress ratio R_i is given by,

$$n_{eqivalent} = \left(\frac{\alpha\left(\frac{\sigma_i}{\sigma_{ultimate}}\right)^{0.6-R_i}[\sigma_i(1-R_i)^{1.6_i}]\frac{1}{f_i^{\beta}}\left(n_i^{\beta}-1\right)\phi_{n1}}{\alpha\left(\frac{\sigma}{\sigma_{ultimate}}\right)^{0.6-R}[\sigma_i(1-R\ )^{1.6}\ ]\frac{1}{f^{\beta}}\ \phi_n}+1\right)^{1/\beta} \tag{3}$$

The operational lifetime of the 2.5m composite blade was predicted to be 7 years using the load spectrum and equation (2).

4. TEST RESULTS

Fatigue testing was carried out until the first crack became visible on the blade. Continuing the fatigue process resulted in a white coloured band developing under the skin of the blade close to the transition section as illustrated in figure 3. After the 6th pass of the spectrum, a total of 6509653 cycles, equal to 6 years of operation, a crack about 60 mm long had propagated through the white coloured band, as shown in figure 3.

Figure 3 Early matrix failure and propagated crack and the at the blades root section.

Figures 4 to 7 inclusive show the strains on the gauges 1 to 4 inclusive (see figure 2 for details of gauge location) under each stress level applied to the blade. It should be noted that the number of cycles is the cycle count from the start of the full-scale fatigue test.

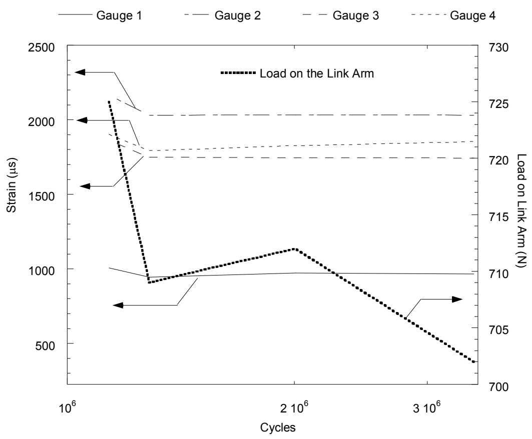

Figure 4 Strain reading on gauges 1 to 4 under the fatigue loading level 100. MPa and load reading on the link arm

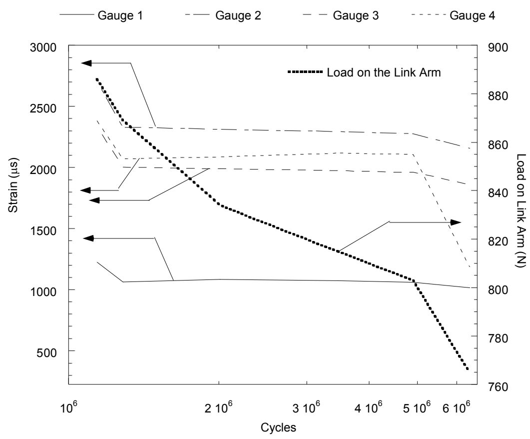

Figure 5 Strain reading on gauges 1 to 4 under the fatigue loading level 112 MPa and load reading on the link arm

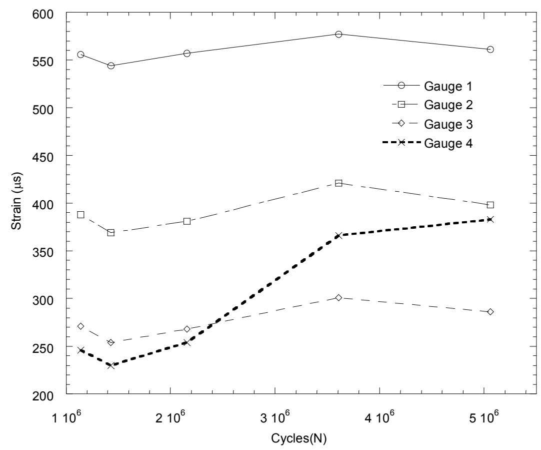

Figure 6 Strains on the gauges 1 to 4 under the load 5kg at the radius of 2300 mm

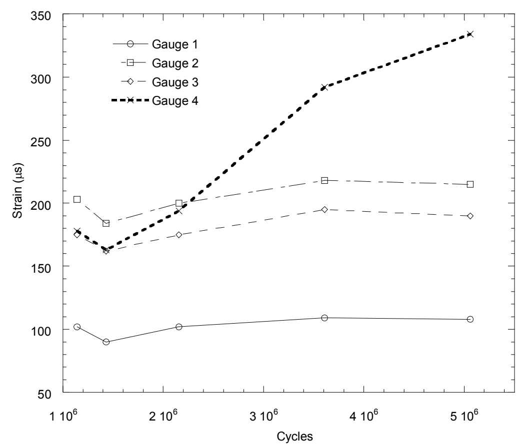

Figure 7 Strains on the gauges 1 to 4 under the load 5kg on the link arm.

5. DISCUSSION OF RESULTS

The 2.5 wind turbine blade was subject to fatigue loading with 6 passes, that is 6 years of equivalent operational life, of spectrum that consisting a total 6509653 cycles at 3 Hz test frequency. The predicted blade life was 7 operational years. After the 2nd pass of spectrum, a white band appeared indicating the start of matrix failure. After the sixth pass of the spectrum (approximately 6509653 Cycles), a 60mm long crack appeared on the pressure side of the blade. This indicates total failure of the composite material at the critical stress location. However the core and the suction surface of the blade shows no evidence of cracking or failure.

During the 2nd pass of spectrum, the force transferred through the link arm dropped by about 4% (maximum), indicating stiffness degradation in the blade structure. Matrix damage may have been initiated at this stage. After the 2nd pass of spectrum, strain readings on gauges G1 to G4, increase monotonically as the blade's material began to rapidly degrade.

The fatigue test rig is a constant displacement system, and as a consequence the strains on the gauges should cyclic between the same limits during testing. However, this was not apparent at low load levels, but does occur at high load levels (above 50 MPa), until a crack appeared on the blade. During the 6th pass of spectrum, the strain readings sudden dropped indicating the crack initiation in the transition section of the blade.

6. CONCLUSION

A 2.5m wind turbine blade has been successfully fatigue tested on a special purpose test rig. A crack started in a region of the blade where the highest stresses were predicted by the detailed finite element model of the blade**.** The predicted life of the blade from equation (2) is in reasonable agreement with the experimental results Further work is needed to assess the material's fatigue properties under both load and displacement control modes to help improve the accuracy of the model.

The failure mode in the blade was not a uni-axial type but was similar to the failure mode in a flexural specimen, Epparachchi (2002). As a consequence the direct use of uni-axial fatigue properties in damage calculation could not be justified by the observations of full scale fatigue testing. This may be one reason for the slight mismatch between the experimentally determined lifetime and the predicted lifetime that used uni-axial fatigue data. However, uni-axial fatigue properties can be used to estimate a conservative solution for blade lifetime whereas flexural fatigue properties may result in an upper bound of the lifetime estimation. Only one full-scale test was done due to time and financial constraints but more full-scale tests are planned for the future.

7. ACKNOWLEDGEMENTS

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